

DOCUMENT RESUME

ED 349 157

SE 052 386

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TITLE Interdisciplinary Approaches to Science Education: A Cognitive Analysis.
PUB DATE 91
NOTE 26p.
PUB TYPE Guides - Classroom Use - Teaching Guides (For Teacher) (052) -- Reports - General (140)

EDRS PRICE MF01/PC02 Plus Postage.
DESCRIPTORS *Cognitive Processes; Elementary Secondary Education; *History Instruction; *Interdisciplinary Approach; *Science Education; *Science History; Science Instruction; Social Studies; *Textbook Content
IDENTIFIERS *Philosophy of Science

ABSTRACT

While many claims have been made about the benefits of interdisciplinary approaches to science education, the contention is that little empirical data exist either to support or refute the claims. The demands of integrated approaches on students or teachers have not been subjected to either theoretical or empirical assessment. This paper presents a first step towards assessing the demands and considers the results of the assessment for the practice of interdisciplinary school science. The analysis is limited to the integration of natural sciences, history, and philosophy. In grades K through 6 or 9, the potential exists for the integrated study of natural sciences. However, from a content analysis of general science and social studies textbooks, topics are expressed serially and fail to expose students to the intellectual relationships among them. The history of science and philosophical foundations of science are poorly integrated in both science and social studies textbooks. In the analysis of tests, another reliable indicator of curriculum, there are few items that explicitly test for student understanding of the intellectual relationships among the natural sciences or their methods of inquiry. The paper discusses the historical case study approach, the problem/issue centered approach to integration, and pedagogical approaches to integration. The posited cognitive outcomes and cognitive demands of integration are presented. (Contains 62 references.) (PR)

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**INTERDISCIPLINARY APPROACHES TO SCIENCE EDUCATION:
A COGNITIVE ANALYSIS**

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Science curriculum theorists and education reformers commend the virtues of interdisciplinary approaches to science education.¹ Integrating the study of science with other academic disciplines, engineering, and art, they claim, produces more advanced levels of scientific literacy, more competent performance in the work place, and better personal and social decisions than do conventional separatist approaches. While many claims have been made for the benefits of interdisciplinary approaches, few have been implemented in U. S. schools at any level. Consequently, little empirical data exist either to support or refute the claims. Neither have the demands of integrated approaches on students or teachers been subject to either theoretical or empirical assessment. Our goal in this paper is to take a first step toward assessing those demands and to consider the implications of the results of the assessment for the practice of interdisciplinary school science.

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The analytical task is difficult for several reasons. Specifications for the practice of interdisciplinary approaches to teaching science are practically nonexistent. Second, outcomes claimed for interdisciplinary approaches are stated in global terms. The third reason, we have already mentioned, is the dearth of practical experience or empirical data about the effects of interdisciplinary courses and programs on student performance. Any thorough assessment of the demands on students and teachers of interdisciplinary approaches requires descriptions of the curriculum and intended outcomes. In the long term, the products of the analysis must be tested against empirical data which will not be available until courses and programs are designed,

implemented, and tested. In the absence of empirical data, we will conduct a logical analysis based on three of the several possible integrated approaches to science.

Approaches to the Organization of Content

The number of possible permutations of interdisciplinary approaches is large including:

- integrated study of the natural sciences — biology, chemistry, physics, and earth science;

- integrated study of a natural science and a social science — sociology, history, economics;

- integrated study of a natural science and other academic discipline — philosophy, mathematics;

- integrated study of a natural science and another area of human endeavor — engineering, art; and

- integrated study of the natural sciences and an academic skill — reading, writing, speaking.

We limit our analysis to the integrated study of the natural sciences, history, and philosophy. Our theoretical analysis posits the influence of the organization of the content and strategies for its presentation on what is learned. First we propose learning outcomes for three different approaches to natural-social sciences content organization which we label conventional, historical, and problem/issue centered. Next, we advance learning outcomes for different pedagogical strategies for the presentation of the content. Then we consider the cognitive and logistical demands that these integrative approaches place on the learner and the teacher. Learner demands are framed in the context of the quantity of cross-disciplinary information the learner is expected to integrate and the diversity of inquiry strategies the learner is expected develop. The demands on the teacher are framed in terms of the instructional decisions that are required to implement interdisciplinary

approaches, that is for the teacher to optimize the choice of content organization, and pedagogical strategy with the learning characteristics of the students.²

Conventional Organization of Content

School and college curricula reflect the value society places on cross-disciplinary understanding. Although the K-16 curriculum leaves open the possibility to afford students the opportunity to develop cross-disciplinary understanding, the organization of schools and the intellectual structures of the disciplines act as barriers to teaching that integrates the disciplines. The diagram in Figure I represents the typical pattern of course offerings in grades K-16 in the natural sciences, social studies, and philosophy. The natural sciences and the social sciences are a part of the curriculum throughout formal schooling. Philosophy is a part of the collegiate program only. The diagram indicates that no formal integration of the natural and social sciences occurs in at the school level. This pattern typically continues through college with one exception. During the senior year at some institutions, a capstone course may be offered that integrates course work across several disciplines. Horizontal integration across natural and social science or philosophy courses at either the school or university level is atypical.

Within courses that comprise the natural science curriculum opportunities abound for integration of the natural sciences. The conventional K-6 science program is on the surface at least interdisciplinary. At these grade levels, students study topics from the biological, physical, and earth and space sciences. This pattern continues through grades 7-9 in some programs while in others the "layer cake" approach begins at grade 7 with the curriculum devoted to either biological, physical or earth and space science at each of the grade levels. The layer-cake structure is the normal pattern in grades 10-16.³

While we recognize that there is considerable variation in the details of the natural science curriculum, we can make some reasonable estimates about the extent to which students have the opportunity to engage in integrated study. In grades K through 6 or 9, the potential exists for the integrated study of the natural sciences. However, on the basis of the content of general science textbooks, which is the best indicator of the content of school science at the elementary and middle school level, we conclude that the potential is not realized. General science textbooks present topics from biology, the physical sciences, and earth and space science serially and fail to expose students to the intellectual relationships among them. Textbooks do not describe or explain how transdisciplinary concepts, such as "system," "cause and effect," or "energy" apply across the natural sciences. Neither do the textbooks address the different forms of scientific inquiry that distinguish or cut across the disciplines. Thus our conclusion from general science textbooks is that little horizontal integration across the natural sciences occurs in general science courses. Neither is there any suggestion in biology, chemistry or physics textbooks that any vertical integration occurs across courses presented in the layer-cake pattern.

Similar patterns are evident in social studies programs. K-4 social studies draws on history, geography, and the social sciences (political science, economics, sociology, anthropology), usually in some version of an expanding environments structure (from family to community to region or state). Typically, grade five is U.S. history, and grade six and seven include world geography and history and perhaps state or local history. Grade eight reintroduces U.S. history (as does grade 11) while grades 9 and 10 repeat and presumably extend world geography and history, usually in regional or area studies that incorporate science dimensions. Grade 12 social studies usually

provides electives such as economics and government or advanced placement history courses.

There is little evidence in either textbooks (still the mainstay of social studies instruction) or studies of social studies classroom practice of explicit horizontal or vertical integration, within or across courses, of content from history, geography, and the social sciences (or of the disciplines themselves). Disjointedness is more characteristic of social studies education than integration.

Science textbooks at all but the earliest grade levels do contain some reference to the history and philosophy of science. The presentation of the history of science typically is limited to biographical sketches, usually one per chapter, of the scientists responsible for the elucidation of the scientific principles presented in the chapter. Little, if any, information about the historical context of the discovery or the development and change over time of a scientific idea is included in the typical science textbook at any grade level. Thus, the history of science is a poorly integrated add on to the science curriculum.

Neither is the history of science a well integrated part of the school history program. Using social studies textbooks as our indicators, we conclude that over the course of 13 years, students are unlikely to hear mention of scientific discoveries in their history classes. Technological advances -- for instance, the invention by McCormick of the reaper -- are often mentioned, primarily because of their economic and social impact.

The philosophical foundations of the natural sciences are treated in a similarly disjointed fashion. Typically the philosophical foundations of the natural sciences are presented in the first chapter of a textbook where the scientific method, the nature of scientific inquiry, and the intellectual attributes of scientists are described. The nature of science, once present-

ed, is seldom mentioned again. The students' next encounter with the nature of science is at the beginning of the text for the next year's science course.

Tests are another reliable indicator of the content of the curriculum. Generally speaking, science achievement tests contain few items that explicitly test for the student's understanding of the intellectual relationships among the natural sciences or their methods of inquiry. Furthermore, the historical development of scientific ideas is limited to factual items relating famous scientists and their discoveries. In short, the achievement tests reflect the content of textbooks and presumably what is taught. Even though the drafters of the framework for the most recent science test of the National Assessment of Educational Progress (Educational Testing Service, 1989) acknowledge the importance of the history and philosophy of science to scientific literacy, the test contains few items related to these topics.

In summary, the structure of the conventional school and college curriculum does not preclude approaches to the natural sciences that integrate history and the nature of science. Even so, there is little evidence of such integration taking place even at the college level, in spite of the fact that the publicly stated goals for school science make cross disciplinary understanding a valued component of scientific literacy.

The Historical Case Study Approach

Natural science courses organized around case studies in the history of science are an example of an unconventional approach to science content organization. Courses organized in this way trace the development from antiquity of the contemporary explanations for natural phenomena. Students learn the explanations that were accepted at various periods in time, the correspondence of the explanations with the prevailing philosophy and culture of the times, the origins of dissatisfaction with the prevailing explanation, as well as the critical experiment, and observations that brought about the challenge to the prevailing theory and the acceptance of the new. Natural science is integrated explicitly and meaningfully with its history and philosophy.

Little can be said about this approach in practice at the school level because it has not been incorporated into the school curriculum to any discernable degree despite the fact that in the 1970s student materials for both the school and college levels were published nationally (Conant 1951, Klopfer, 1964-66, and Klopfer and Cooley, 1963.) In those few instances where it has been implemented at either the school or college level, this approach to the natural sciences has essentially been limited to single courses.

Problem/Issue Centered Approaches

Integrated study of the natural sciences also can be approached by way of courses structured around contemporary social and political issues and problems. Abortion is an example of a contemporary social issue amenable to the approach. Inquiry into the scientific aspects of this issue lead to questions about how life is defined in various intellectual communities, the philosophical bases for the definitions, and how these have changed over time.

Methodological questions also arise, as in the case of the controversy over a study of the psychological effects of abortions which the U.S. surgeon general refused to release because he judged it to be methodologically flawed. The organization of science education around problems provides the opportunity for bringing the perspectives of many disciplines to bear on contemporary problems and issues.

Various pedagogical approaches to foster cross-disciplinary understanding might be used with each of these three ways of organizing the subject matter of the natural sciences, history and philosophy of science.

Pedagogical Approaches

The cognitive components of cross-disciplinary understanding are knowledge and mental processes. Pedagogical approaches to the development of knowledge and processing capabilities reflect underlying conceptions, however vague or tacit, of the nature of the learner and of learning. Conventional pedagogy is based on the passive-absorber conception of the learner. The pedagogical task is to transmit knowledge from the expert to the learner. Lectures, reading, and recitation are the pedagogical methods of choice. A growing body of research challenges the passive-absorber or predetermined knowledge conception and characterizes learners as active-constructors of their own knowledge (von Glasersfeld, 1987). Conventional wisdom as well suggests that better structured knowledge and superior mental capabilities derive from active engagement by the learner. Thus, the pedagogical task is engage the learner in challenging activities that foster information processing, knowledge construction, and knowledge organization. Working in small groups on significant projects is the pedagogical method of choice.

The principles of constructivist pedagogy seem to conflict with conventional views of the value of presenting content structured according to the tenets of the discipline (or, to say it another way, to structure the content in the

ways in which experts in the field structure it (Chi, Feldovitch, and Glaser, 1981)). We have no simple answer to this quandary. We simply acknowledge the power of knowledge structured as experts structure it and leave open the question of which pedagogical methods in which combination and sequence might achieve both cognitive goals -- a well structured knowledge base and the mental capability to operate on that knowledge base.

Conventional approaches to teaching science combine conventional methods of structuring content with conventional methods of pedagogy -- lectures, reading, end-of-chapter problems, and laboratory. While laboratory and problem-solving can be conceived of as tasks requiring active engagement of the learner, all too often, students are intellectually engaged only minimally. End of chapter problems have only academic significance for the student, and the laboratory is simply sequence of activities performed under the direction of a laboratory manual.

The case study approach structures the content to be presented in an unconventional way, but typically transmits the content in conventional ways.

Problem centered approaches are unconventional with respect to both the structure of the content and pedagogy. We recognize of course, that it is conceivable that teachers might lecture to students about a significant contemporary problem or issue, however, the essence of the problem centered approach is active engagement by the learner in the problem or issue. At this point it is appropriate to note that reading, listening to lectures, and doing laboratories are activities appropriate to the problem or issue centered approach. However, engagement in these activities is motivated by the overarching goal, to solve the problem or to resolve the issue. Thus the student has a problem or issue-related purpose for engaging in the activity which makes the activity meaningful and likely to foster learning.

As we noted above, active engagement by the student is necessary to foster well structured knowledge bases and better cognitive capacity. Furthermore, if the problem or issue has significance for the student, constructivists contend that students will be engaged more readily.

Posited Cognitive Outcomes

We turn now to the cognitive outcomes (Greeno, 1976) of the three interdisciplinary approaches to the natural sciences. This analysis is based on two assumptions: (1) that with the "right" pedagogical approaches, students can come to canonical understanding of the subject matter and (2) that students mental capabilities develop as the result of social interaction, that is by observing adults and peers, mimicking their processes, and refining the skills via feedback. Our approach is to describe outcomes cognitively rather than behaviorally as educational goals are typically cast. Cognitive outcomes refer to the contents of mind, knowledge structures and information processing capabilities.

For the purpose of analysis we sort knowledge into two categories, declarative and procedural. Declarative knowledge is knowledge about ..., while procedural knowledge is knowledge how to Knowledge about the natural world and about products of scientific inquiry is declarative knowledge. The processing capacity required to inquire, to solve problems or to make decisions, is procedural knowledge. The distinction is an important one especially with regard to scientific inquiry. Knowing about scientific inquiry is very different from being able to engage in scientific inquiry, which in turn is quite different from being disposed to engage in scientific inquiry.

Declarative Knowledge From Discipline Based Content Organization

The diagram in Figure II represents the cognitive outcome posited for approaches that organize natural science, social science, and philosophy subject matter according to the tenets of the discipline. At the end of 16 years of study, the cognitive products are both declarative and procedural knowledge. The declarative knowledge is organized by discipline and within each discipline is structured according to that discipline's tenets. The declarative knowledge base also contains cross disciplinary knowledge, knowledge about the intellectual relationships among the disciplines -- the features they have in common and the features that distinguish them. (We recognize that, in practice, knowledge may not be structured and that cross disciplinary knowledge may be minimal.)

Table I contains a coarse-grained representation of discipline structure for the natural sciences. The representation is in the form of a list of the major categories of declarative knowledge for the natural sciences. Discipline structured study should produce similarly structured declarative knowledge bases for philosophy and history. One major difference, of course, is the category for the discipline's empirical base. While science is built on observations of the natural world, documents, diaries, and physical artifacts are the data for historical and philosophical inquiry.

Knowledge across the disciplines -- concepts and schemata. As we noted previously, a possible and valued outcome of interdisciplinary organization of content is transdisciplinary understanding of concepts. Certain concepts are a part of the structures of several disciplines. Time is an example of such a concept. Each of the natural sciences has its particular conception of time -- geological time, deep time, light years, very long periods of time -- are typical of earth and space sciences. In contrast particle physicists routinely operate with time periods measured in infinitesimally small units, nanoseconds. Historical time is a social construction imposed after the fact

— middle ages, World War I. All of these and other meanings of time build on the same basic ideas but each has particular aspects unique to its disciplinary purpose. Interdisciplinary approaches provide the opportunity for the development of rich conceptions of transdisciplinary concepts.

We posit that the disciplinary organization of subject matter produces a second level of declarative knowledge, that is, knowledge about disciplines. This in contrast to knowledge about a specific discipline. This knowledge is schema based. Schemata are generic mental frameworks which serve to organize information about a number of instances of a concept in a systematic way that serves as a guide for learning about a new instance of the concept. Thus, a schema for discipline serves to organize information about the common features of a number of disciplines and serves as a guide for learning about an unfamiliar discipline. A schema for discipline knowledge contains places for the discipline's concepts, principles, and theories. A nature-of-the-discipline schema contains places for the discipline's goals, philosophical basis, and modes of inquiry.

Schemata are powerful mental tools. They enhance learning and the transfer of knowledge to new situations. Schemata develop only after intellectual engagement with a number of instances of a concept. A schema for academic discipline, for instance, can only develop after engagement with several instances of disciplines.

The Case Study Approach

The knowledge base that develops for the case study approach to the history of science will be quite different from that engendered by exposure to content organized according to the tenets of the disciplines. (For examples of materials taking this approach see Conant, 1951, Klopfer, 1964-66, and Klopfer and Cooley, 1963.) Figure III is a diagram for a course that organizes science content according to the development of scientific ideas. Case studies in the example are drawn from physics, biology, chemistry, and geology. The major conceptual eras in each case study are identified by the name of a scientist and arrows between the names signal that a change in perspective occurred.

Presumably, the knowledge structure resulting from this approach would be composed of sub-structures for each of the major periods in the development of the modern theory containing (1) the empirical information that the period perspective was based on, (2) the major concepts, principles and theories used to explain observations of the natural world, and (3) assumptions about the natural world and the philosophical basis for the natural sciences as they were practiced at the time. Presumably the case study approach to classical mechanics produces similarly organized period structures for major periods in the development of our currently held ideas of the motion of objects -- including the Aristotelian, Galilean, and Newtonian perspectives. These mini-knowledge structures are integrated into a larger structure for the historical development of explanations for the motion of macroscopic objects. Developed in this way, the resulting body of knowledge is organized according to historical development and is quite different structurally from a body of knowledge about kinematics organized according to the contemporary interpretation of the discipline's body of knowledge.

An element common across each of the case studies in our diagram and an element common to any historical study, is the process by which ideas change over time. Thus, the case study approach is likely to produce a well developed schema for the process of change of scientific theories. In the specific instance of the change from an Aristotelian to the Newtonian perspective, the student would know the factors that brought about the downfall of the old theory and fostered acceptance of the new one. Studying a number of different cases would enable the development of schema for changes in scientific theory. The case study organization of content has the advantage of bringing to the foreground the processes by which scientific theories change over time. However, this gain is at the expense of the development of a broad knowledge of the natural sciences or of one of the natural sciences in particular. The case study approach would produce an historically structured knowledge base about mechanics, but little knowledge about other topics in physics — light, heat, or modern atomic theory — unless they also become the topical focus of a case study.

The Problem or Issues Based Approach

This approach brings a number of disciplines to bear on a topic or issue of contemporary interest (See for example, American Chemical Society, 1988; Lujan and White, 1989). Abortion, global warming, solid waste management and depletion of the ozone layer are examples of contemporary problems around which the content of the natural sciences, history and philosophy might be organized. In the case of abortion, history and philosophy are two disciplines appropriate to both the technical and ethical analysis of the issue. Knowing the historical development of contemporary definitions of what constitutes human life as well as the philosophical views of human control over human life illuminate the contemporary dilemma. The knowledge base

developed in this approach has attributes in common with that developed in the case study approach. Just as in the case study approach, where a number of mini-knowledge structures related to different perspectives held over time develop, in the problems/issue based approach, mini-structures related to different points-of-view on the issue or problem develop. For instance, different theoretical perspectives on the causes of global warming are likely content for knowledge structures developing from the study of global warming.

The feature common across the problems or issues studied is the use of discipline based knowledge for problem solving and issues resolution. Just as the case study approach highlights the process of theory change, the problem/issue centered approach highlights knowledge utilization. Thus the approach is likely to engender understanding of the relevance of disciplinary knowledge to contemporary problems and issues as well as the ability to bring disciplinary knowledge to bear on them.

Procedural Knowledge

Thus far we have considered the relationship of the structural organization of content and the development of declarative knowledge structures. We are equally concerned with students' capacity for the effective utilization of knowledge to learn, to inquire, to reach personal decisions, and to solve problems. The requisite cognitive capabilities to engage in these activities are extensive. A chart listing some of them is presented in Figure IV. The list is long, and the interaction of the component cognitive processes and the knowledge base on which they operate is complex. But rather than dwelling on these complexities, we will assess theoretically how different pedagogical approaches affect the development of a well structured knowledge base and the cognitive capabilities to act on that

knowledge base to learn, to inquire, to solve academic and real-world problems, and to make personal decisions.

The chart in Figure IV shows the relationship between academic tasks and procedural outcomes. It is based on the assumption that the process of engaging in academic tasks under the tutelage of an expert, the teacher, develops cognitive processing capacity. The types of academic tasks listed include solving problems, learning, and inquiry. Listed under the major heading, generic, are thinking abilities that are common to all three types of academic tasks. Listed under the major heading, task specific, are thinking abilities that are particular to problem solving, learning, and inquiry.

The chart is incomplete in several respects: (1) the component abilities for many of the tasks are not enumerated; (2) it includes only academic tasks particular to science instruction, and (3) it does not include the more complex tasks likely to be encountered outside the classroom. For instance, the component abilities listed under inquiry in the chart are specific to scientific inquiry. Historical inquiry has some features in common with scientific inquiry. However, apparatus selection and use are not typical of historical inquiry.

Different pedagogical approaches will enhance the development of different cognitive processes. Conventional pedagogical methods will develop information processing skills required for reading, managing information, and comprehending lectures. An inquiry approach to historical case studies should contribute to the development of information processing skills required for historical inquiry. The problem solving/inquiry resolution approach will develop processing skills required for the execution of these tasks.

Two conclusions we can draw from this brief cognitive analysis of the procedural knowledge outcomes are (1) that competencies we expect to develop from integrated approaches to science are extensive and complex, and (2) that

no single pedagogical approach is adequate to the development of all the desirable skills.

The Cognitive Demands of Interdisciplinary Approaches

The cognitive demands of interdisciplinary study on students and teachers are great. Among the challenges students face are those of developing transdisciplinary understanding of concepts as well as coming to understand the knowledge bases and inquiry methods of more than one discipline.

Teachers and program designers face a complex of instructional decisions. For instance:

At what point in the education sequence should students first be exposed to cross-disciplinary ideas?

When is it appropriate to introduce young children to the ideas of physical space-time?

When is it appropriate to introduce young children to the idea of historical time?

When is it appropriate to expect students to grapple with the similarities of physical and historical conceptions of time?

Which aspects of time are best taught in the context of the natural sciences? which in the context of history?

When can students be expected to understand abstract concepts such as discipline and inquiry?

What are appropriate strategies for maintaining a balance between the cognitive goal for a well structured knowledge base and adequate procedural knowledge?

How does the developmental level of the students factor into decisions regarding the balance of cognitive goals and exposure to cross-disciplinary ideas?

What are appropriate problems for interdisciplinary inquiry at the elementary, middle, and senior high school?

When is it appropriate to engage students in the historical case study approach?

In addition to these instructional planning decisions, teachers face myriad instructional decisions on-stage, some of which are particular to the success of interdisciplinary approaches to science teaching. For instance:

Given limited time (and perhaps other resources on a particular day), do I focus on physics principles, the relationships of physics to some other natural or social sciences or to the history and philosophy of physics, or on procedures for solving physics problems?

What are parallels in the other natural or social sciences that I might use to illustrate the transdisciplinary nature of science in this case? What examples best illustrate important differences (in knowledge or mode of inquiry) among the sciences in this case?

Clearly, teachers need to become more knowledgeable or knowledgeable in different ways than in the past in order to integrate school science in ways meaningful to students and authentic to established science.

As our analysis demonstrates, the potential for interdisciplinary approaches to develop powerful knowledge structures and cognitive capabilities is high. However, the potential will not be realized unless instruction is carefully planned with attention to the cognitive demands of the curriculum and the experiential and developmental limitations of the students. For this to occur, teachers and curriculum designers must be better informed about the demands of the curriculum on the students and teachers, as well as the relationships among content organization pedagogical methods and the development of knowledge structures and cognitive capabilities.

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END NOTES

¹ See for example: American Association for the Advancement of Science, 1989; American Association for the Advancement of Science, 1990; British Council/World Bank, 1989; Bybee, et al., 1989; Department of Education and Science and the Welsh Office, 1985; Hickman, et al., 1987; National Governors' Association, 1990; Berlin, 1990; Brown, 1977; Jacobs, 1989; Koballa, et al., 1984; Neumann, 1988; Penick, et al., 1984; Rosenthal, 1984.

² We recognize that the demands on both students and teachers are not solely cognitive. The demands on teachers, for example, also are social and political as various stakeholders in science education push for their version of school science. See P. J. Gaskell (in press). For the purposes of this paper, however, we focus on cognitive demands.

³ The National Science Teachers Association's Scope, Sequence and Coordination project sponsors several sites across the country experimenting with restructuring science in grades 6-12 from the "layer cake" configuration to the European strand configuration.

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